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Preliminary fluid-inclusion microthermometry study of fluid evolution and temperature-pressure conditions in the Goldcorp High-Grade zone, Red Lake mine, Ontario[1]

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GSC Quebec, Québec

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Abstract: Fluid-inclusion microthermometry was done on a barren carbonate vein and a gold-rich silicified carbonate vein. Fluid immiscibility is indicated by the coexistence of carbonic and aqueous inclusions in both carbonate and auriferous quartz. Primary fluid inclusions in the carbonate indicate CO_2 dominance in the carbonic phase, homogenization temperatures of aqueous inclusions range from 191.8° to 343.9°C, and fluid pressures from 129 to 1448 bars. Primary fluid inclusions in auriferous quartz indicate significant amounts of CH_4 in addition to CO_2 in the carbonic phase, homogenization temperatures of aqueous inclusions range from 252.1° to 380.1°, and fluid pressures from 882 to 2436 bars. The study documents a systematic change in fluid composition and inferred temperature-pressure conditions from carbonate-vein formation, through auriferous silicification, to post–main-stage mineralization, euhedral quartz, and gold remobilization. The carbonate veins and silicification formed at similar temperatures, but at significantly different fluid pressures, which may indicate a) a difference in formation depths, b) a change of fluid regime from hydrostatic to lithostatic, or c) post-trapping modification of fluid inclusions.

Résumé : On a procédé à l'analyse microthermométrique des inclusions fluides dans un filon de carbonates stérile et dans un filon de carbonates silicifié riche en or. La coexistence d'inclusions carboniques et aqueuses aussi bien dans les carbonates que dans le quartz aurifère est un indice de l'immiscibilité des fluides. Les inclusions fluides primaires dans les carbonates indiquent la dominance de CO_2 dans la phase carbonique; les températures d'homogénéisation de ces inclusions aqueuses se situent entre 191,8 °C et 343,9 °C à des pressions des fluides variant de 129 à 1 448 bars. Les inclusions fluides primaires dans le quartz aurifère montrent des quantités appréciables de CH_4 qui s'ajoutent à celles en CO_2 dans la phase carbonique; les températures d'homogénéisation de ces inclusions aqueuses se situent entre 252,1 °C et 380,1 °C à des pressions des fluides variant de 882 à 2 436 bars. L'étude démontre un changement systématique de la composition des fluides et des conditions de température et de pression déduites, depuis la formation des veines de carbonates, puis de la silicification aurifère, de la formation de quartz automorphe ultérieure au stade principal de minéralisation et, enfin, de la remobilisation de l'or. La formation des filons de carbonate et la silicification se sont déroulées à des températures semblables, mais à des pressions des fluides nettement différentes ce qui pourrait indiquer : a) une différence dans les profondeurs de formation, b) un changement du régime des fluides, d'hydrostatique à lithostatique, ou c) une modification des inclusions fluides, subséquente à leur piégeage.

[1] Contribution to the Western Superior NATMAP Project

INTRODUCTION

The world-class Campbell–Red Lake gold deposit in the Red Lake greenstone belt is one of the largest and richest Canadian Archean gold deposits (>18 000 000 oz Au). The deposit is well known for its high grades and complex mineralization styles and history. The Goldcorp High-Grade zone at the Red Lake mine, one of the two mines exploiting the deposit, is one of the highest grade gold mineralizations known, with 1.7 Mt of reserves (proven and probable) grading 69.347 g/t Au (Northern Miner, October 1–7, 2001). The average grade mined in the Goldcorp High-Grade zone since the beginning of its extraction exploitation is 88 g/t Au (Northern Miner, June 18–24, 2001). It is of both scientific and economic significance to study the geological processes responsible for such high-grade ore.

The Campbell–Red Lake deposit is a very complex deposit and its genesis is the subject of a continuing debate. Penczak and Mason (1997) and Damer (1997) proposed a premetamorphic low-sulphidation epithermal origin, whereas Andrews et al.(1986), Rogers (1992), Zhang et al.(1997), Tarnocai et al.(1998), and O'Dea (unpub. rept., 1999) opted for a synmetamorphic-syntectonic origin. A pre- to syn- to late-deformation multistage model was proposed by MacGeehan and Hodgson (1982).

As an integrated part of the study of the Goldcorp High-Grade zone at the Red Lake mine, fluid-inclusion microthermometric analyses were carried out on a few key samples representing different stages of mineralization. The purpose is to provide an initial idea regarding the fluid characteristics before, during, and after the gold mineralization, in order to better understand how the deposit was formed and contribute to the ongoing debate on its genesis.

Fluid inclusions were studied from three different mineral phases: pre-ore carbonate, syn-ore quartz, and post-ore (?) euhedral quartz and associated carbonate. The necessity to study fluid inclusions in the pre-ore carbonate is due to the fact that these carbonate veins show excellent crustiform textures that were interpreted as indicators of shallow epithermal environments (MacGeehan and Hodgson, 1982; Penczak and Mason, 1997). Therefore, it is of key importance to estimate the temperature-pressure (T-P) conditions under which they formed from fluid inclusions. However, it is necessary to point out that fluid inclusions in carbonate, compared to those in quartz, are more prone to post-trapping modification. Prior to this study, published fluid-inclusion work was limited to gold-associated quartz from the Campbell mine, and only carbonic inclusions were studied (Tarnocai and Hattori, 1996).

It is assumed that primary fluid inclusions in quartz associated with gold represent the mineralizing fluids from which gold is directly associated, based on megascopic examples of gold intimately hosted in quartz, replacing barren carbonate veins (Dubé et al., 2001a, b, 2002).

REGIONAL AND LOCAL GEOLOGICAL SETTING

The Red Lake greenstone belt is dominated by Mesoarchean rocks including the volcanic-dominated Balmer (2.99 Ga), Ball (2.94–2.92 Ga), and Bruce Channel (2.894 Ga) assemblages. These Mesoarchean rocks were tilted by a pre-D_1 episode of deformation, and were separated by an angular unconformity from the ca. 2.75–2.73 Ga Neoarchean volcanic rocks of the Confederation assemblage (Sanborn-Barrie et al., 2001). Two main episodes of penetrative deformation (D_1, D_2) took place after the ca. 2.74 Ga volcanism (Sanborn-Barrie et al., 2001), resulting in two sets of folds (F_1 and F_2) and associated foliations (S_1 and S_2).

The Campbell–Red Lake gold deposit is mainly hosted by tholeiitic basalt of the Balmer assemblage (Fig. 1). The geometry of rock units at the Red Lake mine is characterized by alternating southeast-trending F_{2a} antiforms-synforms, the northeast pair of which are transected by steeply southwest-dipping and southeast-trending faults, including the Dickenson and Campbell faults (Fig. 1). The Goldcorp High-Grade zone occurs in the hinge zone of an F_{2a} antiform (Dubé et al., 2001a, 2002) (Fig. 1). The volcanic units and the high-grade ore zones are cut by feldspar porphyries and lamprophyre dykes (*see* Dubé et al., 2001a, 2002 for a more complete description of the local geology).

Carbonate (Fe-dolomite-siderite-ankerite) veins are abundant. These veins are commonly barren or contain low-grade mineralization associated with sphalerite (e.g. Penczak and Mason, 1997). In the Goldcorp High-Grade zone, three sets of barren carbonate sheeted and breccia veins, hosted by foliated basalt, can be distinguished (Dubé et al., 2001a, 2002). The first set, and by far the most common, is southeast-trending and moderately southwest-dipping. The second strikes south-southeast, and dips southwest, whereas the third set is east-west trending. Irrespective of their orientation, most veins and breccias show colloform-crustiform banding and cockade texture (Fig. 2A, B, C).

The various sets of carbonate veins are deformed. Depending on their original orientation relative to S_2, the carbonate veins were deformed by asymmetric boudinage or they were folded by small-scale southeast-trending F_{2b} folds (Dubé et al., 2002).

Gold mineralization in the Goldcorp High-Grade zone is associated with arsenopyrite-rich silicic replacement of carbonate veins and breccias, as well as enclosing wall-rock selvages, with variable amounts of hydrothermal magnetite and stibnite and trace to 5% fine pyrite and/or pyrrhotite with rare sphalerite. Significant high-grade mineralization is located at the intersection of the south-southeast-trending and the southeast-trending carbonate veins and host structures forming silicified and arsenopyrite-rich southwest-plunging ore shoots (Dubé et al., 2001a, 2002).

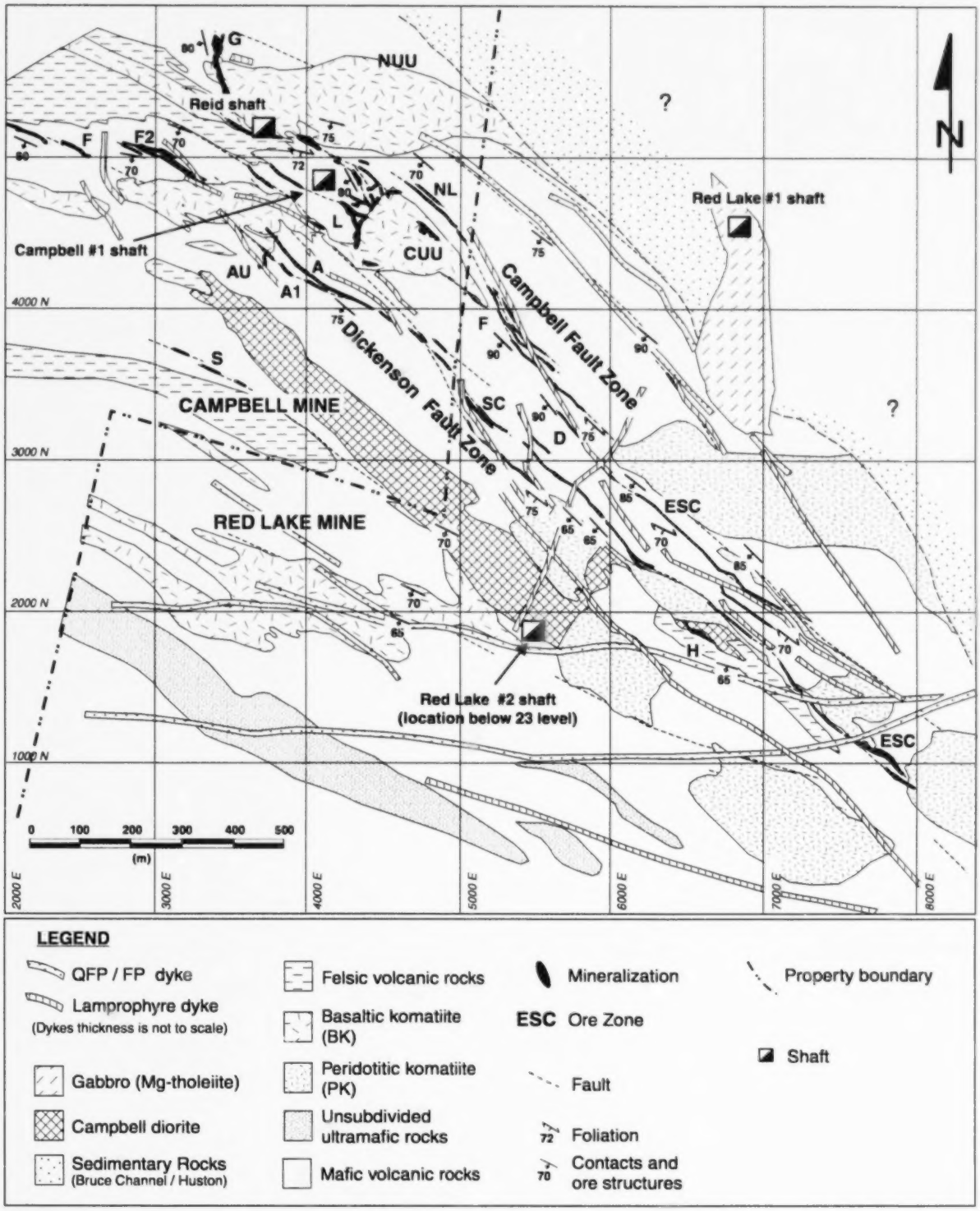

Figure 1. *Geological map of the Cambell–Red Lake gold deposit* (modified from *Goldcorp Inc. geological data*).

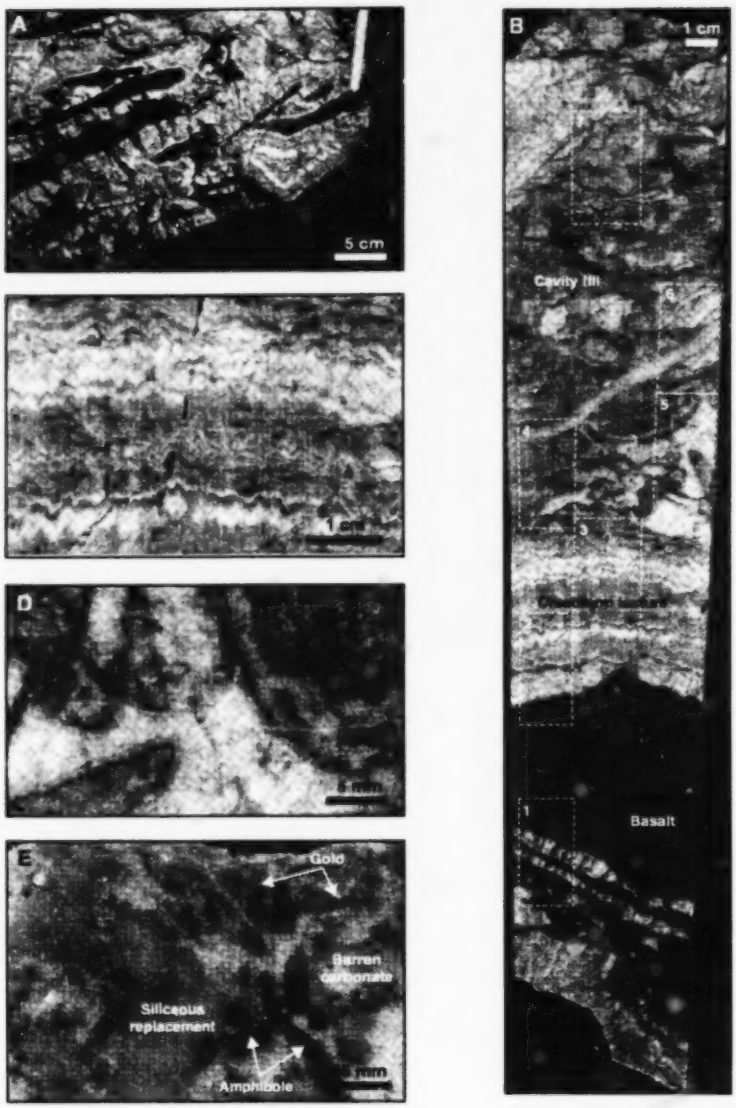

Figure 2.

(A) Colloform and cockade textures in a carbonate extensional breccia vein; section view. (B) Sample KG-2000-50, showing well developed crustiform and cavity filling textures in a carbonate vein hosted by basalt. (C) Close-up of the crustiform textures showed in Figure 3B. (D) Close-up of sample KG-2000-50-5. (E) Sample KG-2000-11, showing gold associated with siliceous replacement of barren carbonate.

Late north-south-striking and shallowly dipping barren extensional quartz veins are locally present. They are mostly confined within late lamprophyre dykes. They are essentially composed of euhedral quartz crystals with some carbonate oriented perpendicular to the vein walls. These veins postdate the main stage of gold mineralization. Euhedral, barren quartz crystals are also developed in residual pores in the carbonate veins or in veinlets cutting the carbonate veins.

Late gold remobilization is demonstrated by visible gold coating and filling fractures hosted within a steeply dipping lamprophyre dyke (Dubé et al., 2002).

PETROGRAPHY OF THE SAMPLES FOR FLUID-INCLUSION STUDY

Three samples were selected for this preliminary fluid-inclusion study. Samples KG-2000-50 and KG2000-45 were collected from carbonate veins with well developed crustiform texture (Fig. 2B, C, D). Sample KG-2000-11 was from a strongly silicified carbonate vein with abundant visible gold (Fig. 2E). Seven doubly polished thin sections were prepared from KG-2000-50 (Fig. 2B), but only one of them (KG-2000-50-5; Fig. 2D) was studied for microthermometry because it was the only one that contained well defined primary fluid inclusions along carbonate growth zones.

Petrography of the selected samples indicated that there are at least two generations of carbonate: a) an early nonluminescent phase, and b) a yellow-luminescent phase under cathodoluminoscope. The nonluminescent phase is much more abundant and is commonly cut or coated by the yellow-luminescent carbonate. The latter is also associated with local euhedral barren quartz. Layers of fibrous carbonate commonly form bands adjacent and parallel to wall rock at the contact with veins as well as concentric bands enveloping wall-rock fragments enclosed in the veins. These carbonate bands are followed by millimetre- to centimetre-wide coarser, anhedral calcite, both being nonluminescent. It was locally observed that the yellow-luminescent carbonate cut across some amphibole and was associated with chlorite in the gold-bearing zones. The nonluminescent carbonate is commonly deformed and shows slight to moderate undulose of extinction, whereas the yellow-luminescent carbonate and associated euhedral quartz show uniform extinction to slight undulation.

The quartz hosting the ore is fine grained and anhedral. It shows slight to moderate undulose of extinction and commonly replaces both generations of carbonate. Gold occurs as individual grains along grain boundaries of quartz, or occasionally as trails of rounded grains along microfractures. Some minor carbonate veinlets cut across the auriferous quartz and clearly indicate late stage CO_2-rich fluid (e.g. Penczak and Mason, 1997; Dubé et al., 2001a).

FLUID-INCLUSION PETROGRAPHY AND MICROTHERMOMETRY

In sample KG-2000-50-5, primary fluid inclusions distributed along growth zones are commonly seen in coarse, anhedral, nonluminescent carbonate. The growth zones are shown by alternating high- and low-population bands of fluid inclusions which follow the euhedral shape of carbonate crystals (Fig. 3A). Fluid inclusions randomly distributed in three dimensions within this phase of carbonate are common. These fluid inclusions are possibly primary, but they were not studied because of the availability of better defined fluid inclusions (i.e., those in growth zones). The euhedral quartz and associated yellow-luminescent carbonate are relatively free of fluid inclusions. The fluid inclusions occurring in them are scattered; they are considered as primary or pseudo-secondary fluid inclusions.

In sample KG-2000-11-1, both primary and secondary fluid inclusions occur in quartz. The primary fluid inclusions are those which occur alone; it is not uncommon that a single fluid inclusion occurs in an individual quartz crystal (Fig. 3B). The secondary fluid inclusions are those distributed along microfractures. These microfractures are commonly short, usually terminating within or at the boundaries of individual quartz crystals. Secondary fluid inclusions along longer microfractures crosscutting multiple quartz grains are uncommon. Secondary fluid inclusions were initially not the target of this study. However, it was found that some rounded gold grains were distributed along the same

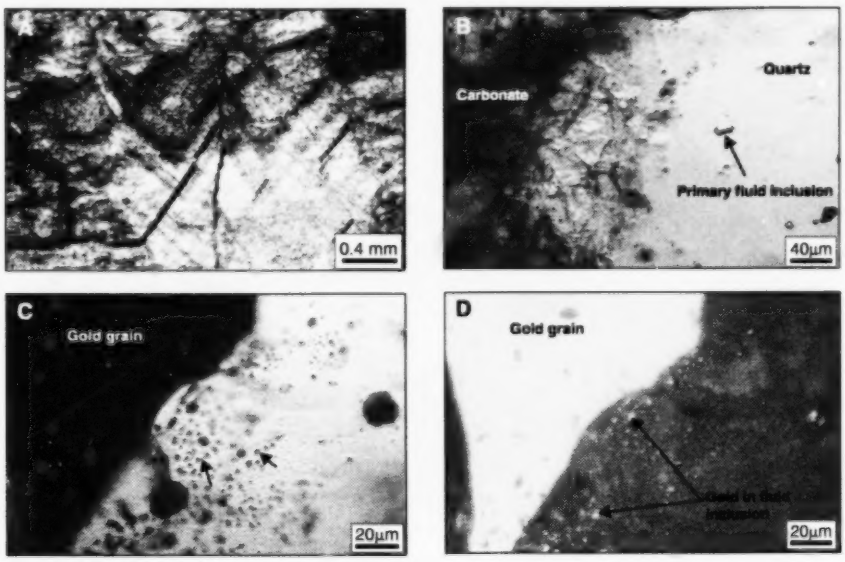

Figure 3. *(**A**) Primary fluid inclusions distributed along growth zones (KG-2000-50-5); (**B**) An isolated fluid inclusion in quartz (KG-2000-11); (**C**) Secondary fluid inclusions associated with rounded gold grains in the microfracture in quartz near a larger gold grain. Gold grains are wrapped or connected by fluid inclusions (arrows). (**D**) Same as figure 3C, but under reflectance light. Note some gold grains inside fluid inclusions.*

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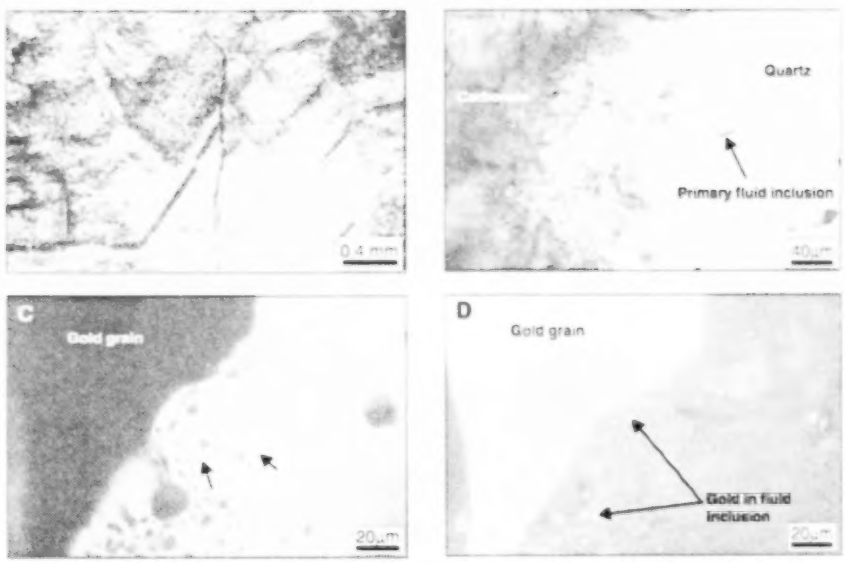

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Table 1. Fluid-inclusion microthermometric data.

Sample no.	Host mineral	Occurrence of fluid inclusions	Size (μ)	T_m-first (°C)	T_m-clathrate (°C)	T_h-carbonic (°C)*	T_h-final (°C)
KG-2000-50-5	Carbonate - I	Growth zone	9	-56.7	-	+30.4 L**	-
		Growth zone	7	-56.8	-	+29.4 L	-
		Growth zone	9	-	-	-	204.0
		Growth zone	8	-	-	-	319.5
		Growth zone	10	-56.7	-	+27.7 L	-
		Growth zone	6	-56.6	-	+23.3 L	-
		Growth zone	7	-56.6	-	+25.2 L	-
		Growth zone	4	-56.9	-	+26.2 L	-
		Growth zone	3	-56.8	-	+26.4 L	-
		Growth zone	9	-56.7	-	+29.4 L	-
		Growth zone	5	-56.6	-	+27.6 L	-
		Growth zone	5	-56.6	-	+27.7 L	-
		Growth zone	3	-56.6	-	+25.2 L	-
	Carbonate - I	Growth zone	8	-57.0	-	+27.2 V	-
		Growth zone	8	-57.0	-	+27.8 L	-
		Growth zone	5	-57.0	-	+29.1 L	-
		Growth zone	6	-56.7	-	+22.7 V	-
	Carbonate - I	Growth zone	5	-56.9	-	+28.7 V	-
		Growth zone	5	-56.9	-	+26.8 L	-
		Growth zone	6	-56.9	-	+30.6 L	-
		Growth zone	8	-56.7	-	+25.9 L	-
		Growth zone	6	-56.7	-	+29.0 L	-
		Growth zone	6	-56.6	-	+27.6 L	-
		Growth zone	7	-56.7	-	+25.1 L	-
		Growth zone	6	-56.6	-	+25.3 L	-
		Growth zone	5	-56.8	-	+27.1 L	-
		Growth zone	5	-56.7	-	+18.7 V	-
		Growth zone	6	-56.7	-	+15.6 V	-
		Growth zone	5	-	-	-	191.8
	Carbonate - I	Growth zone	18	-	+26.8	-	343.9
		Growth zone	11	-	-	-	245.7
		Growth zone	9	-	-	-	293.3
		Growth zone	10	-	-	-	312.4
		Growth zone	8	-57.0	-	+30.4 L	-
	Carbonate - I	Growth zone	7	-56.6	-	+26.3 L	-
		Growth zone	6	-56.7	-	+21.8 L	-
		Growth zone	7	-56.7	-	+26.6 L	-
		Growth zone	7	-57.0	-	+28.4 L	-
		Growth zone	5	-56.9	-	+26.4 L	-
		Growth zone	6	-56.8	-	+26.5 L	-
		Growth zone	6	-56.7	-	+27.9 L	-
		Growth zone	9	-57.0	-	+26.9 L	-
	Carbonate - I	Growth zone	15	-	-	-	315.0
	Carbonate - II	Isolated	12	-	+15.6	-	188.6
		Isolated	9	-	+18.2	-	131.6
	Quartz - II	Scattered	9	-	+27.8	-	126.6
		Scattered	13	-	+28.7	-	169.8
		Scattered	14	-	+28.2	-	129.0
		Scattered	30	-	+28.4	-	183.6
		Scattered	15	-	+28.6	-	72.6
		Intracrystal trail	18	-	-	-92.6 V (CH4)	-
		Intracrystal trail	10	-	-	-98.5 V (CH4)	-
KG-2000-11-1	Quartz - I	Isolated, near gold grain	9	-58.0	-	+11.5 L	-
		Isolated, near gold grain	8	-58.2	-	+4.8 L	-
	Quartz - I	Isolated, near gold grain	6	-57.3	-	+14.0 L	-
		Isolated, near gold grain	5	-57.3	-	+19.8 L	-
	Quartz - I	Isolated	7	-57.9	-	+16.7 L	-
	Quartz - I	Isolated	8	-57.2	-	+20.1 L	-
	Quartz - I	Isolated	15	-57.2	-	+13.5 L	-
		Isolated	14	-57.2	-	+14.4 L	-
	Quartz - I	Cluster	5	-	-	-	331.8
			5	-57.0	-	+16.6 L	-
			5	-57.4	-	+16.3 L	-
			6	-59.2	-	+22.1 L	-
			8	-57.3	-	+8.5 L	-
	Quartz - I	Isolated	12	-	+15.4	-	330.4
		Isolated	5	-57.0	-	+26.5 L	-
	Quartz - I	Isolated	9	-	-	-	380.1
	Quartz - I	Intracrystal trail	8	-	-	-	252.1
			18	-	-	-	307.7

*: CO_2 inclusions unless specified as CH4 inclusions
**: L = liquid, V = vapor

microfractures as secondary fluid inclusions; some of these fluid inclusions contain a gold grain within the inclusions (Fig. 3C, D). Therefore, these secondary fluid inclusions were also studied for microthermometry.

The microthermometric measurements were carried out on a United States Geological Survey (USGS) heating/freezing stage located at GSC Quebec. The accuracy and precision of the measurements of melting and homogenization temperatures of carbonic phases are about ± 0.2°C, whereas those of total homogenization temperatures are around ±1°C. The microthermometric results are listed in Table 1.

In all the mineral phases examined, carbonic fluid inclusions are much more abundant than aqueous fluid inclusions. The carbonic inclusions are mainly dominated by CO_2, with variable amounts of other gases such as CH_4. Some fluid inclusions in euhedral quartz show homogenization temperatures lower than -82.1°C (critical temperature of CH_4); they are likely dominated by CH_4. Although the carbonic fluid inclusions appear to contain only one or two carbonic phases at room temperature, theoretically they must contain an aqueous phase. This aqueous phase may occur as a thin film near the inclusion wall, and may not be observable under microscope. All the examined aqueous inclusions did not show obvious freezing during cooling runs down to -190°C. No ice-melting temperatures can be measured with certainty. However, clathrate-melting temperatures were measurable in many of the aqueous inclusions. Fluid inclusions containing both observable carbonic and aqueous phases are less abundant than carbonic inclusions. These inclusions commonly did not homogenize at the same temperatures as the aqueous inclusions; they are most likely heterogeneously trapped inclusions, and their homogenization temperatures are unusable.

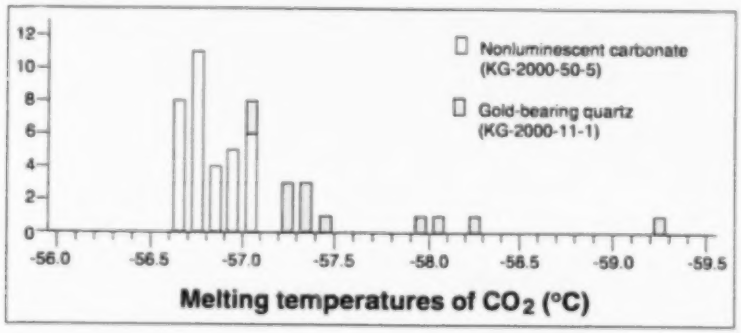


Figure 4.

Histogram of melting temperatures of CO_2.

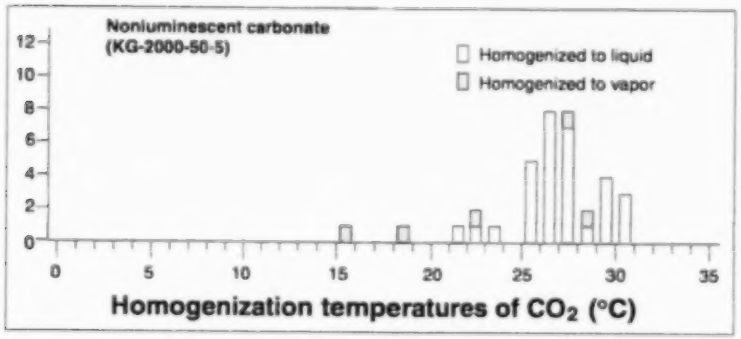
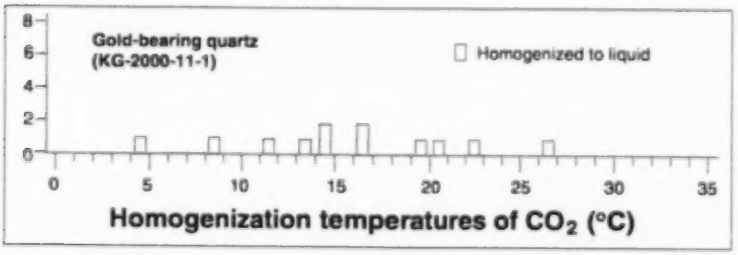


Figure 5.

Histogram of homogenization temperatures of CO_2.



Fluid inclusions in the crustiform nonluminescent carbonate

Carbonic fluid inclusions distributed along growth zones in coarse, anhedral, nonluminescent carbonate are either monophase or biphase at room temperature. The melting temperatures of CO_2 range from -56.6° to -57.0°C (Fig. 4; Table 1), indicating that the fluid is dominated by CO_2. The homogenization temperatures of CO_2 range from 15.6° (to vapour) to 30.4°C (to liquid) (Fig. 5; Table 1).

Aqueous inclusions associated with the carbonic inclusions show homogenization temperatures ranging from 191.8° to 343.9°C (Fig. 6; Table 1). Melting temperatures of ice cannot be determined. The melting temperature of clathrate was measured for one inclusion at +26.8°C (Table 1).

Inclusions containing both carbonic and aqueous phases did not homogenize at temperatures up to 350°C. No further microthermometric measurements were attempted.

Although carbonic inclusions can either homogenize into the liquid or vapour phase, both occur in the coarse, anhedral nonluminescent carbonate; they generally do not occur in the same growth zones. Although there are more measurements of carbonic inclusions homogenized into the liquid phase (Fig. 5), it should be noted that monophase carbonic inclusions are abundant. Many of these monophase inclusions did not show observable liquid carbonic phase during cooling runs; they are most likely carbonic inclusions that homogenize to the vapour phase at low temperatures.

Primary fluid inclusions in quartz associated with gold

Primary carbonic fluid inclusions in quartz associated with visible gold, typically in isolation in individual quartz crystals, are mainly monophase at room temperature. During cooling runs, a vapour bubble nucleates that homogenizes into the liquid phase at temperatures ranging from 4.8° to 26.5°C (Fig. 5; Table 1). The melting temperatures of CO_2 range from -57.0° to -59.2°C (Fig. 4; Table 1), indicating that the fluid contains a significant amount of CH_4 in addition to CO_2.

Aqueous inclusions associated with the carbonic inclusions show homogenization temperatures ranging from 252.1° to 380.1°C (Fig. 6; Table 1). Melting temperatures of ice cannot be determined. The melting temperature of clathrate was measured for one inclusion at 15.4°C (Table 1).

Inclusions containing both carbonic and aqueous phases did not homogenize at temperatures up to 380°C. No further microthermometric measurements were attempted.

Secondary fluid inclusions in quartz associated with gold

Secondary fluid inclusions in quartz associated with visible gold occur in microfractures usually terminating at crystal boundaries. Some of these microfractures contain trails of rounded gold grains, and some of the gold grains were wrapped by the fluid inclusions (Fig. 3C, D). These fluid inclusions are monophase at room temperature, and appear to be similar to other carbonic inclusions. However, during cooling to -196°C, no phase change was observable. It is suspected that these inclusions contain carbonic phase of very low density.

Primary fluid inclusions in euhedral, barren quartz and associated carbonate

The euhedral quartz and associated carbonate occur either as open-space filling in residual pores in the crustiform carbonate or as veinlets cutting the crustiform carbonate. Both carbonic and aqueous inclusions occur in euhedral quartz crystals.

The carbonic inclusions, occurring in a short microfracture within the quartz crystal, are interpreted as pseudosecondary inclusions. They are monophase at room temperature, and nucleate a liquid phase while cooling. The liquid phase homogenizes into the vapour phase at temperatures ranging from -92.6° to -98.5°C (Table 1). These are most likely methane inclusions of low density.

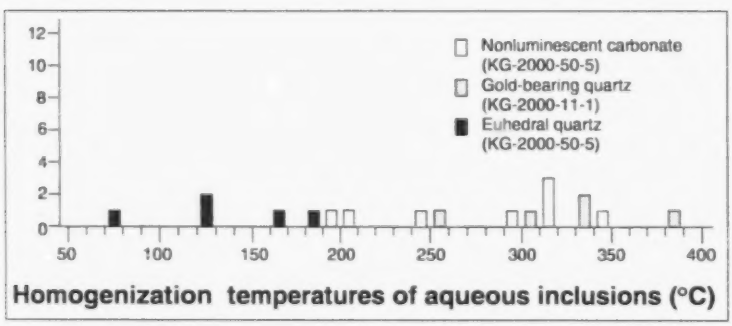


Figure 6.

Histogram of homogenization temperatures of aqueous inclusions.

The aqueous inclusions, scattered within the quartz crystal, show variable vapour/liquid ratios ranging from 5 to 70%, suggesting heterogeneous trapping. The aqueous inclusions with vapour/liquid ratios lower than 10% show homogenization temperatures ranging from 72.6° to 183.6°C (Table 1; Fig. 6). Despite the relatively large sizes of the inclusions (up to 30 μm; Table 1), ice-melting temperatures cannot be determined. During cooling to -196°C, no freezing was observable; instead, the vapour bubble gradually expanded to double the size at room temperature, and the boundary between the inclusion and quartz crystal became vague. When the temperature came back to -73.2°C, the bubble suddenly expanded into 'cracks' in the aqueous phase, suggesting that the aqueous phase was frozen. With further warming, some grainy textures were observed in the aqueous phase, but no ice crystals were distinguished. A last melting event can be observed at temperatures between 27.8° and 28.9°C (Table 1); these temperatures probably represent the melting of clathrates. Although a very slow heating rate (0.4°C / minute) was used, these relatively high melting temperatures are probably metastable temperatures because no such clathrate was observed before the cooling runs. Melting of methane clathrate at temperatures as high as 28°C implies fluid pressures as high as about 500 bars (*see* Seitz and Pasteris, 1990), or high density of methane, which is contradictory to the observation of low homogenization temperatures of methane inclusions into the vapour phase. However, the melting temperatures of 27.8° to 28.9°C are compatible with that of H_2S clathrate, which breaks down at 29.5°C in the H_2O-H_2S system, and are comparable to the observation of Bény et al. (1982) which indicated H_2S clathrate melting temperatures between 25° and 27°C.

A few aqueous inclusions in carbonate associated with euhedral quartz show homogenization temperatures ranging from 131.6° to 188.6°C, and melting temperatures of clathrate ranging from 15.6° to 18.2°C (Table 1).

INTERPRETATION OF THE MICROTHERMOMETRIC DATA AND DISCUSSION

Fluid immiscibility

The abundance of carbonic inclusions without observable aqueous phases, and the coexistence of aqueous inclusions with some carbonic + aqueous inclusions, in the various mineral phases examined in this study, suggest that there were two immiscible fluid phases during the precipitation of these minerals. The carbonic inclusions, which theoretically contain an aqueous phase that is unobservable under microscope, represent the vapour phase, whereas the aqueous inclusions represent the liquid phase. The carbonic + aqueous inclusions likely represent heterogeneous trapping of both the liquid and vapour phases at the moment of fluid-inclusion entrapment.

It is not known whether the two immiscible fluids resulted from an in situ phase separation from a single parent fluid, or if they were derived from a fluid flow that contained two fluid phases, already separated (?), before arriving at the site of mineral precipitation. The fact that carbonic inclusions are much more abundant than aqueous inclusions seems to favour the latter interpretation. In this case, the carbonic phase is preferentially carried in the two-phase flow.

Temperature-pressure conditions of carbonate vein formation and silicification

Based on the inference of fluid immiscibility presented above, the homogenization temperatures of fluid inclusions formed from homogeneous trapping represent the temperatures of the fluids at the moment of entrapment. The carbonic inclusions probably formed from homogeneous trapping of the vapour phase, but their temperatures of total homogenization cannot be measured. The aqueous inclusions probably formed from homogeneous trapping of the liquid phase, and their homogenization temperatures are used to indicate the trapping temperatures. The homogenization temperatures of carbonic phases in carbonic inclusions are used to construct isochores, using the Flincor program of Brown (1989), and the pressures on the isochores corresponding to the homogenization temperatures of aqueous inclusions are used to indicate the fluid pressures at the moment of fluid inclusion entrapment.

The isochores of carbonic inclusions in the crustiform carbonate, approximated by a pure CO_2 system, indicate a very large variation in fluid pressures (Fig. 7A). Fluid pressures vary from 129 to 841 bars at 191.8°C (the minimum homogenization temperature of aqueous inclusions), and from 189 to 1448 bars at 343.9°C (the maximum homogenization temperature of aqueous inclusions). The variation in fluid pressures at a given temperature is more than that which could have been caused by a change in the pressure system between lithostatic and hydrostatic loads. Therefore, unless a change between supralithostatic and under-hydrostatic systems is assumed, some of the pressure values could have resulted from post-trapping modification of the fluid inclusions, considering the relatively unstable nature of the host mineral (carbonate). Given the limited amount of data at this stage of the study, we temporarily take the median of the pressure range (dashed line in Fig. 8) to represent the fluid pressures, which range from 485 bars at 191.8°C to 818 bars at 343.9°C. These median pressure values correspond to a depth of 4.9 to 8.3 km if a hydrostatic load (density = 1 g/cm^3) is assumed, or 1.8 to 3.1 km if a lithostatic load (density = 2.7 g/cm^3) is assumed.

The carbonic inclusions in the quartz associated with gold are also approximated by a pure CO_2 system because the amount of CH_4 cannot be quantified with microthermometry. The calculated isochores also indicate a large variation of fluid pressures (Fig. 7B), ranging from 882 to 1722 bars at 252.1°C (the minimum homogenization temperature of aqueous inclusions), and from 1306 to 2436 bars at 380.1°C (the maximum homogenization temperature of aqueous inclusions). The work of Tarnocai and Hattori (1996) on gold-associated quartz from the Campbell mine, with CO_2 homogenization temperatures ranging from 8° to 13°C , presumably to the liquid phase, also indicate high fluid

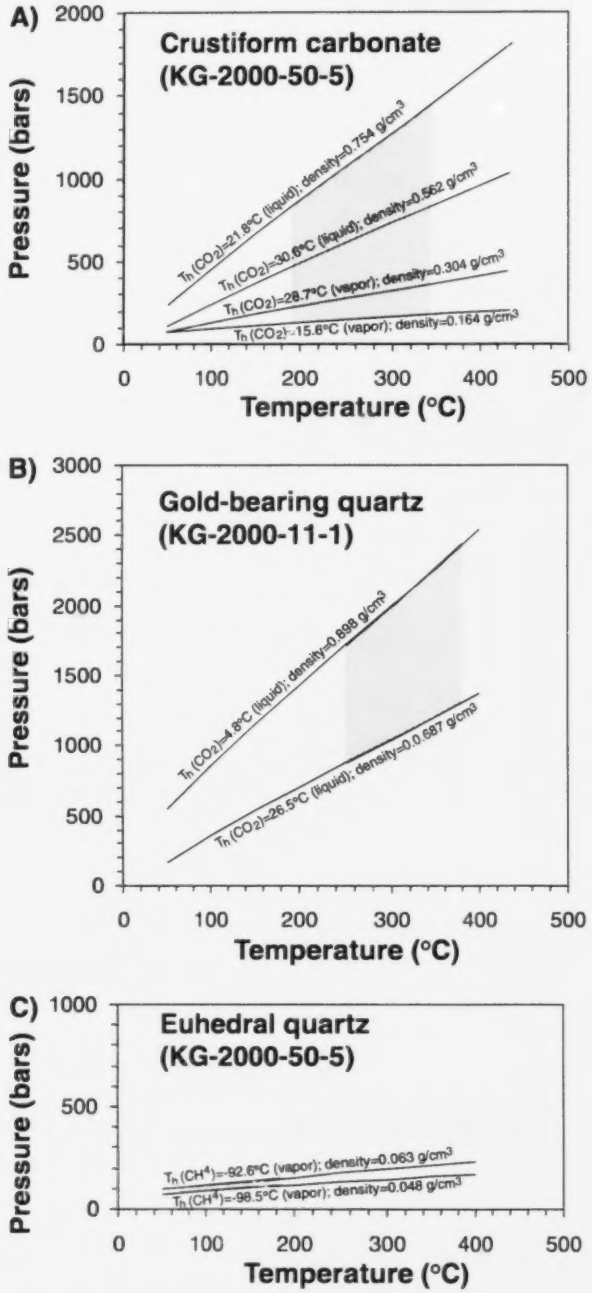


Figure 7. Isochores of carbonic fluid inclusions. The shaded areas indicate the range of temperatures inferred from aqueous inclusions and the range of estimated fluid pressures.

pressures. The variation in fluid pressures at a given temperature can be explained by a change in the pressure system between lithostatic and hydrostatic load, although again the possibility of post-trapping modification of fluid inclusions cannot be ruled out. The median of the pressure range (dashed line in Fig. 8) ranges from 1302 bars at 252°C to 1871 bars at 380.1°C. These median pressure values correspond to a depth of 4.9 to 7.1 km if a lithostatic load (density = 2.7 g/cm^3) is assumed; a hydrostatic system is considered unlikely at these pressure values.

From the limited homogenization-temperature data of aqueous inclusions, there appears to be a major overlap in terms of temperature between the formation of the carbonate veins and silicification, i.e., 191.8° to 343.9°C for the former, and 252.1° to 380.1°C for the latter (Fig. 8). However, there is a significant difference in calculated fluid pressures between carbonate and silicification, although there is an overlap (Fig. 8). There are two possible explanations for the pressure difference between the carbonate veins and the auriferous silicification. One is that they formed at different depths. In such a scenario, and assuming a lithostatic load, the median pressure values determined for the carbonate stage suggest that they could have formed at less than 3 km from surface and consequently could be compatible with a low-sulphidation epithermal environment as suggested by their pristine colloform-crustiform texture (e.g. Penczak and Mason, 1997). In such a case, the very large variation in fluid pressures would require a fluctuation during the carbonate stage between supralithostatic and underhydrostatic pressure regime. In the second possibility, the carbonate and silicification stages could have formed at similar depths, but under different pressure regimes: hydrostatic during the carbonate deposition and lithostatic during the silicic replacement of the already-formed carbonate veins as the system was sealed by these veins. In such a case, the variation in fluid pressure estimated from fluid inclusions within the carbonates could have resulted from post-trapping modifications of the fluid inclusions. At this stage of the study, we cannot rule out either possibility. Further studies will be done to confirm the nature of fluid pressure variation.

Temperature-pressure conditions of euhedral-quartz formation

The homogenization temperatures of aqueous fluid inclusions in euhedral quartz range from 72.6° to 183.6°C. Based on the inference of fluid immiscibility, these homogenization temperatures represent the temperatures of precipitation of euhedral quartz. The carbonic inclusions are approximated by a pure CH_4 system. The calculated isochores indicate pressure values ranging from 80 to 105 bars at 72.6°C, and from 112 to 149 bars at 183.6°C (Fig. 7C). These pressures correspond to depths from 0.8 to 1.5 km if a hydrostatic regime is assumed, or from 0.3 to 0.6 km if a lithostatic regime is assumed.

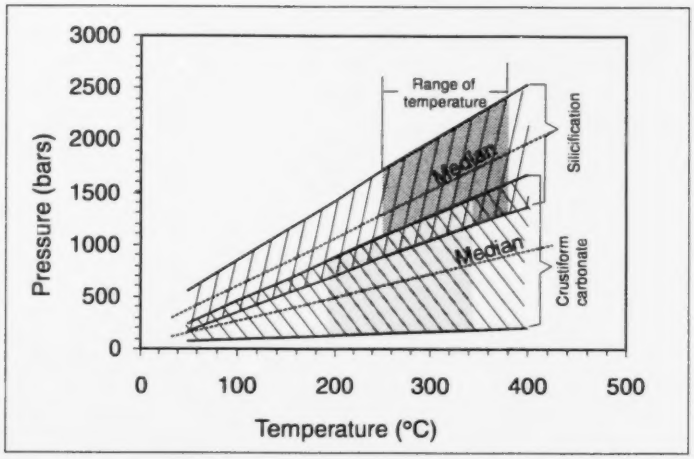


Figure 8.

Comparison of inferred T-P conditions between carbonate vein formation and silicification. Note the major overlap in temperature and the significant difference and small overlap in fluid pressure.

There is a significant fluid pressure drop from auriferous silicification to euhedral-quartz formation. Although no microthermometric data have been obtained from the secondary fluid inclusions that contain gold grains, we infer from the behaviour of these inclusions during cooling runs that they are low-density carbonic inclusions and were possibly formed under similar condition as the euhedral quartz. Therefore, the gold grains associated with these secondary fluid inclusions probably represent remobilization of gold after the main stage of gold emplacement (e.g. Dubé et al., 2002).

Evolution of fluid composition

From the melting temperatures of CO_2 (Fig. 4), it is obvious that there was a compositional change from carbonate-vein formation to silicification. The fluids associated with carbonate-vein formation are dominated by CO_2, whereas those associated with silicification contain significant amounts of other gases (most likely CH_4) in addition to CO_2. Such a change in composition probably reflects a difference in fluid sources or evolution of the same fluid system due to change of redox conditions induced by progressive reaction of the fluid with the host rocks. In the Campbell mine, Tarnocai and Hattori (1996) noted that the fluid inclusions from high-grade ores contain larger amounts (3–7 mole %) of CH_4 than those from low-grade ores (less than 2 mole %). The predominance of methane inclusions in euhedral quartz indicates a further change in fluid composition after the main-stage mineralization. The implication of this change in fluid composition and T-P conditions after mineralization will be the subject of further investigations.

The composition (CO_2 and CH_4) and T-P (252–380.1°C; 1302–1871 bars) of the quartz related to the main stage of gold-bearing silicification of the carbonate vein and host rocks share some analogies with, although they are absolutely not diagnostic of, those associated with quartz-carbonate shear-zone-hosted gold systems in ancient deformed terranes. In such a case, as the carbonate veins and silicification formed at relatively similar temperature, the significant variations in pressure could be related to the transition from hydrostatic (during the carbonate deposition) to lithostatic (supra-lithostatic) regimes during the silicic replacement of the already-formed carbonate veins as the system was sealed by these veins. But, based only on the preliminary fluid-inclusion information gathered from the carbonate vein (191.8°–343.9°C and 485–818 bars), the possibility that these carbonate veins were formed in a low-sulphidation epithermal environment cannot be ruled out.

The homogenization-temperature data of aqueous inclusions (252° to 380.1°C) in the quartz related to the main stage of gold-bearing silicification suggest that the temperature of the hydrothermal fluid was lower than the amphibolite-grade peak-metamorphic conditions recorded by the rocks in the mine, estimated by Damer (1997) at a pressure ranging between 1 to 2.2 kb and a temperature between 435° and 550°C. This may suggest diachroism between mineralization and peak-metamorphic conditions. The mineralization could be pre-peak metamorphic conditions or associated with retrograde-cooling post-peak metamorphism. The limited fluid-inclusion data gathered and the number of samples studied remain significantly too limited to be conclusive.

CONCLUSIONS

This preliminary study documents a systematic change in fluid composition and inferred T-P conditions from carbonate-vein formation, through silicification + gold mineralization, to post-main-stage mineralization euhedral-quartz formation. The fluid-inclusion microthermometric data indicate that the carbonate veins and silicification formed at similar temperature conditions, but at different fluid-pressure conditions. This difference in fluid pressures may indicate a difference in formation depths, or may reflect a change of fluid regime from hydrostatic to lithostatic. The main uncertainty is whether the variation of fluid pressures indicated by fluid inclusions within the carbonate reflects a real pressure variation during the precipitation of the carbonate, or it is caused by post-trapping modification of the fluid inclusions. Further detailed microthermometric studies from other samples will help clarify this uncertainty. Nevertheless, these

preliminary results clearly indicate a) there were two immiscible fluid phases during the precipitation of the carbonate and the main stage of gold-rich quartz replacing the carbonate. It is not known whether the two immiscible fluids resulted from an in situ phase separation from a single parent fluid, or if they were derived from a fluid flow that contained two fluid phases before arriving at the site of mineral precipitation. b) There is significant change in fluid pressure and composition from carbonate-vein formation to gold-associated silicification. These results remain preliminary, as the data gathered are too limited and their significance needs to be further examined in the context of deposit-scale hydrothermal, geological, and structural evolution.

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